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Goliath Frog (*Conraua goliath*) abundance in relation to frog age, habitat, and human activity

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***Abstract.*—Habitat change and overexploitation are major factors driving species population declines worldwide, and they often act in union. The Goliath Frog, *Conraua goliath,* is an iconic species that is known to be extensively exploited by humans. However, Goliath Frog populations have not yet been assessed quantitatively in relation to their proximity to human settlements, nor has the loss of terrestrial habitat adjacent to the frogs' riverine habitat been investigated. In this study, populations of the Goliath Frog were assessed across its range in Cameroon during nocturnal, time-constrained, visual encounter surveys. Goliath Frogs showed a patchy distribution along torrent rivers in three main habitat types: primary forest, secondary forest, and agroforestry plantations. There were no significant differences in the encounter rates among the three habitat types. However, we noted higher frog abundances, including larger sized adults, with increasing distance from human settlements, an observation confirmed by local frog hunters. Our observations revealed strong segregation in microhabitats with respect to age classes, as juvenile frogs were frequently found along river beds with rock pools/rock crevices, while sub-adults were mostly encountered around exposed rocks at river rapids, and adults were mostly recorded near cascades and waterfalls. The adults predominately perched on rocks around waterfalls and rapids, with distances of about 3–5 m between them, suggesting both territoriality and site fidelity. Adults were observed foraging at night, beyond 10 m from the river bank. During the day, adults were seen basking on rocks along the river bank. The lower abundance and size of Goliath Frogs near human settlements indicates the effects of hunting pressure, with terrestrial habitat showing less of an effect on this species. Monitoring of the remaining Goliath Frog populations, raising local awareness on the effects of hunting and habitat preservation, as well as law enforcement, are suggested as further efforts to conserve the world's largest frog species.**

Keywords. Amphibia, Anura, Cameroon, conservation, exploitation, habitat choice, monitoring, threatened species

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Introduction

The world's biodiversity crisis is almost exclusively due to human activities, most notably the conversion and destruction of natural habitats. However, the overexploitation of many species, such as for food, is an increasingly serious threat as well. Frogs are no exception to this trend (Mohneke et al. 2010; Altherr et al. 2022), and both of these threats may also affect the world's largest frog, *Conraua goliath* (Boulenger 1906). This species is restricted to southwestern Cameroon and northern Equatorial Guinea, where it occurs in lowland to mid-altitude rainforests below 1,000 m asl (Lamotte and Perret 1968; Sabater-Pi 1985; Wild et al. 2004; Stuart et al. 2008; Channing and Rödel 2019). This frog is associated with fast flowing rivers and larger streams with rocky outcrops, rapids, and waterfalls (Perret 1957; Amiet 1975; Sabater-Pi 1985; Gewalt 1996; Herrmann et al. 2005). These natural habitats are becoming progressively altered through various human activities, such as conversion to farmland, construction of roads and hydroelectric dams, and exploitation for artisanal and commercial timber resources. The combination of logging and conversion of the remaining forests to agroforestry plantations has tremendous negative consequences on biodiversity, including amphibians. The

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progressive fragmentation of original forest landscapes leads to modified microclimates with obvious adverse effects on amphibian communities (e.g., Ernst et al. 2006; Stuart et al. 2004, 2008; Ernst and Rödel 2008; Hillers et al. 2008; Ofori-Boateng et al. 2013). Previous studies suggested that fragmentation and destruction of habitat has led to a reduction in Goliath Frog populations at various Cameroonian sites (Amiet 2004; Herrmann et al. 2005). If this is true, it is likely that these processes would cause general population decline over the entire range of the species. In addition, frog meat may be an important (or at least a much valued) protein source for many indigenous people throughout the Goliath Frogs' range (Gonwouo and Rödel 2008). Hence, the increasing human population, expansion of settlements and increased efficiency of hunting tools will intensify the pressure on this species. This is especially evident in the professionalized hunting methods (traps, hooks, spears, throwing nets, etc.) that have been developed specifically to collect Goliath Frogs (Amiet 2004; Gonwouo and Rödel 2008; Schäfer et al. 2019). The hunt for subsidiary consumption, as well as for local bush meat markets, might be one of the main factors driving the population decline of Goliath Frogs. The commercial harvesting of *Hoplobatrachus occipitalis* has contributed to the population decline of this species in northern Bénin (Mohneke et al. 2010). Based on its rarity and much larger size (assuming a longer time until frogs become mature), similar or even more severe consequences may be assumed for the Goliath Frog. As a result of these pressures, this species is currently listed as Endangered by the IUCN and Class A under Cameroonian law (IUCN Amphibian Specialist Group 2019a; NLG et al., unpub. data).

Previous studies on the Goliath Frog have focused mostly on its distribution (Perret 1957, 1960; Sabater-Pi 1962, 1967; Amiet and Perret 1969; Gewalt 1977), taxonomy, and phylogeny (Lamotte and Perret 1968; Nguiffo et al. 2019; Blackburn et al. 2020). Some investigations have also investigated various aspects of life-history, including larval development, parasites, and reproduction (Lamotte et al. 1959; Perret 1957, 1960; Sabater-Pi 1985; Nguiffo et al. 2015). Parental care has recently been documented in the species (Schäfer et al. 2019), and additional studies by the authors of this paper are in progress to further improve our knowledge of the life-history of this species. However, very little is known concerning the population trends and habitat preferences of this species, or the specific threats that this species is facing. In the absence of research on the habitat requirements and responses to the various threats facing the Goliath Frog, the development and implementation of appropriate conservation measures are difficult.

To remedy this general lack of knowledge, this study examines the impact of land use and proximity to human settlements on the relative abundance, demographics, and body size of Goliath Frogs. The data presented in this paper are based on six years of investigations on the Goliath Frogs in Cameroon, and allow us to examine the correlations between this species and human-caused forest alteration and to propose the directions and goals of future research and conservation strategies.

Material and Methods

Study Area

Fieldwork was carried out from November 2014 to December 2019 during both rainy and dry seasons (Table 1), although the dry seasons (November to February) were emphasized as the rivers were more accessible. Fieldwork focused on the areas around three main localities in south-western Cameroon: Moungo, Sanaga maritime, and Nkam division (Littoral region); Nyong-Ekele (Central region); and Bipindi in Ocean division (South region) (Fig. 1). In total, 13 rivers (Table 1) were surveyed, including the Nkam and Sanaga rivers.

Investigations were carried out from near sea level around Kribi (Ocean division), up to the foothills of Mount Manengouba near Nkongsamba (Moungo division). The latter locality hosts the northernmost population of the Goliath Frog and is characterized by several large rivers and streams. Overall, the landscapes of our sites constituted mostly low to medium elevation habitats, with the elevations of our frog observations ranging from 39 m asl along Lobe River (Bifa, Ocean division) to about 677 m asl along Nkam River (Nkoungsou, Moungo division). Other than the Moungo area, which is characterized by a heterogeneous, mountainous landscape (Mts. Kupe, Nlonako, Manengouba), the remaining sample localities have a low-rise or flat relief, only rarely interrupted by hills. The study areas comprised a mixture of several large forest patches of Guinea-Congolian lowland rainforest (both pristine and logged), agroforestry plantations, and small-scale subsidiary agricultural sites. Especially in the area around Yabassi (Nkam division), logging companies commercially exploit timber for exportation, despite the remoteness and difficulty in accessing the area. The entire study region has a tropical climate, with the wet season extending from March to October and the dry season from November to February. Rainfall peaks in August and September, and the driest period extends from late December to the end of February. The annual precipitation ranges from 2,000 to 3,000 mm (Amiet 1975).

Surveys and Data Acquisition

The visual encounter survey (VES) method (Heyer et al. 1994; Rödel and Ernst 2004) was used in suitable habitats to systematically survey for Goliath Frogs. The VES consisted of counting all Goliath Frogs encountered in every major habitat type, and provided an encounter rate per person-hour. Three major habitat types were

Table 1. River sites investigated for Goliath Frogs in three surveyed habitat types in western Cameroon. The information provided includes river name, total length of sampled trails, geographic position, and a short habitat description (including length of river investigated and the total sampling effort per site in person-hours).

Locality (river name, coordinates, elevation [m asl])	**Date**	**Habitat characteristics (including approximate length surveyed for each section and person-hours of effort for each site)**
Lobe 02°36'47.23"N, 10°01'05.51"E; 39 m asl	17 December 2014	Section one: Composed of logged secondary forest (SF) with open to semi-closed canopy forest which covered about 70% of the surveyed trail, ~250 m. Section two: Small-scale cocoa plantation with few native trees interspersed in the plantation and a relatively open canopy, ~150 m **(9.77 person-hours).**
Nkebe 4°45'25.05"N, 9°58'06.18"E; 231 m asl	14 February 2015	Section one: River bank bordered by primary forest with a closed canopy of native trees that were about 25–30 m high. Open understory including leaf litter on floor. Steep flanks at some sites that were difficult to access, with no signs of human activity, ~1,500 m. Section two: Selectively logged secondary forest along a path with constant human signs. Trees about 25 m high with relatively open to closed canopy. Secondary growth trees observed where logging had been carried out, ~400 m **(13.74 person-hours).**
Ekomtolo 4°47'32.57"N, 9°53'11.60"E; 332 m asl	12 February 2015	Section one: Composed of logged forest along steep portions of the river where farming activities are impossible. Many footpaths present and rampant wood extraction for local furniture and domestic fuel, ~300 m. Section two: Composed of large- to small-scale cocoa plantations with few native trees spaced all over the area and constantly managed by the community. Chemicals used to sustain the crops are processed in the nearby river with possible contamination, ~500 m (**4.25 person-hours**).
Dibombe 4°36'43.46"N, 9°46'42.26"E; 60 m asl	15 February 2015	Forest composed of a mosaic of primary forest, secondary forest, and agroforestry plantation interspersed all through the surveyed trail. Section one: Mainly closed canopy of native trees, about 25–30 m tall, along difficult-to-access terrain, no previous logging had occurred. Forest floor with about 70% leaf litter cover, ~900 m. Section two: Old selectively logged forest, easy access due to the many footpaths present, empty cartridges left behind by hunters, ~400 m. Section three: Small-scale plantation, mainly composed of cocoa and banana plants which covered the flat sections along the river on both flanks, ~300 m (**14.26 person-hours**).
Sanaga Ngo Mpem 4°04'15.42"N, 10°40'14.16"E; 241 m asl	7–12 July 2016	Section one: Primary forest on slopes along the river where movement and tree exploitation is difficult, ~1,000 m. Section two: Included portions where access was easier with several human foot paths present, signs of forest exploitation, ~650 m (**10.55 person-hours**).
Sanaga (Tributary River) 4°03'23.19"N, 10°37'12.88"E; 297 m asl	13–15 July 2016	Section one: Composed of small patches of native large trees around difficult-to-access points of the river, bordered by very large rocks, ~700 m. Section two: Composed of recently logged forest patches, with several hunting paths. Frequent use of the forest to collect non-timber forest products, ~600 m (**14.55 person-hours**).
Keinke 2°52'36.73"N, 10°04'56.75"E; 48 m asl	2–3 March 2017	Section one: Consisted of closed canopy trees of about 25 m in height on both sides of the river. Footpaths present within the forest seem to be regularly used by fishermen and Goliath Frog hunters, ~900 m. Section two: Recently logged forest with open canopy and bushy understory. Regular use of this forest section evident, with many footpaths present, ~200 m (**11.72 person-hours**).

Table 1 (continued). River sites investigated for Goliath Frogs in three surveyed habitat types in western Cameroon. The information provided includes river name, total length of sampled trails, geographic position, and a short habitat description (including length of river investigated and the total sampling effort per site in person-hours).

Locality (river name, coordinates, elevation [m asl])	Date	Habitat characteristics (including approximate length surveyed for each section and person-hours of effort for each site)
Magamba 4°45′19.03″N, 9°52′16.68″E; 308 m asl	6 April 2016	Trail bordered by agroforestry plantations as well as subsistence plantations on both banks. Fallow land present along river bordered by degraded forest with very dense vegetation, edges with shrubs and only a few trees present, ~600 m **(6 person-hours)**.
Nkam 5°08′17.43″N, 9°59′43.17″E; 677 m asl	29 October –2 November 2018	Section one: Consisted of agroforestry plantations, mainly cash crops including coffee, cocoa, and palm oil trees growing on the river bank, ~800 m. Section two: Mainly composed of small relic forest patches on steep valleys along the river, access was difficult. No possibility of farming at this site, but forest patches appeared to have been logged with several foot paths found, ~350 m **(4.96 person-hours)**.
Mbo 4°49’39.16”N, 9°47’18.58”E; 465 m asl	6 April 2016	Section one: Vegetation composed of a mosaic of secondary forest and agroforestry plantations on both river banks. Secondary forest composed of fallow land, more than 10 years old, and several cocoa plants and large palm trees could still be found. Section two: Permanently cultivated plantation with young cocoa and palm trees, intensively managed with signs of constant human presence, ~250 m **(14.97 person-hours)**.
Mpoula 4°38′15″N, 9°43′07″E; 200 m asl	27 February – 5 May 2018	Surveyed trail composed of a mosaic of secondary forest (~200 m) and agroforestry plantation (~300 m) on both sides of the river, constant human activities noted along the trail **(10.8 person-hours)**.
Njuma 4°20’53.1”N, 10°13’56.3”E; 304 m asl	27 August –17 September 2019	River bordered by primary forest (~1,200 m) on both sides with little or no signs of human activity, though foot paths where present and have been used by poachers and seasonally by Goliath Frog hunters **(5.31 person-hours)**.
Bisoue 4°21’38.3”N, 10°12’30.4”E; 152 m asl	27 August –17 September 2019	River bordered by primary forest (~ 400 m) on both sides with little or no human impact. Access was difficult at some points due to the dense undergrowth along old footpaths **(15 person-hours)**.

identified along the 13 rivers: primary or pristine forest (PF; Fig. 2A), selectively logged or secondary forest (SF; Fig. 2B), and agroforestry plantations (AP; Fig. 2C, also see Table 1 and below for detailed descriptions of the habitat types).

Transects along the rivers could comprise either a single vegetation type, or a mosaic of different vegetation types or segments (e.g., PF, SF, and AP) that could vary considerably in short succession. This was especially true when human settlements were nearby. To measure the portion of a certain vegetation type in a single transect, we passed the respective segment and measured the covered distance with a GPS unit. The vegetation type was identified on both sides of the river by assessing the canopy cover (visual estimation to 25% accuracy), estimated height (± 5 m), and measured diameter at breast height (DBH) (± 0.5 cm) of the trees, as well as any obvious human impacts, such as selective logging, hunting, or extraction of non-timber forest products (e.g., leaves, tree bark, fruits, resins, or roots).

Primary Forest (PF) consisted of closed canopy forest with 75–100% canopy cover. This forest type was dominated by large, native trees of about 25–30 m in height, although the largest exceeded 50 cm in DBH. No evidence of recent logging was present in PF. Although hunting or fishing paths were regularly found along the rivers (especially close to human settlements), revealing some degree of natural resource exploitation, this forest type was still considered mature and relatively undisturbed. Primary Forest comprised seven segment portions of the 13 rivers surveyed, and their lengths and brief descriptions are provided in Table 1.

Selectively logged Secondary Forest (SF) included all vegetation formations with a relatively closed canopy (50–75% canopy cover) and medium to large trees (10–25 m in height). Here, the tree composition included both native and non-native tree species with DBH usually exceeding 40 cm, including many secondary growth trees. These forests had been previously logged for commercial timber exportation, and/or by the local

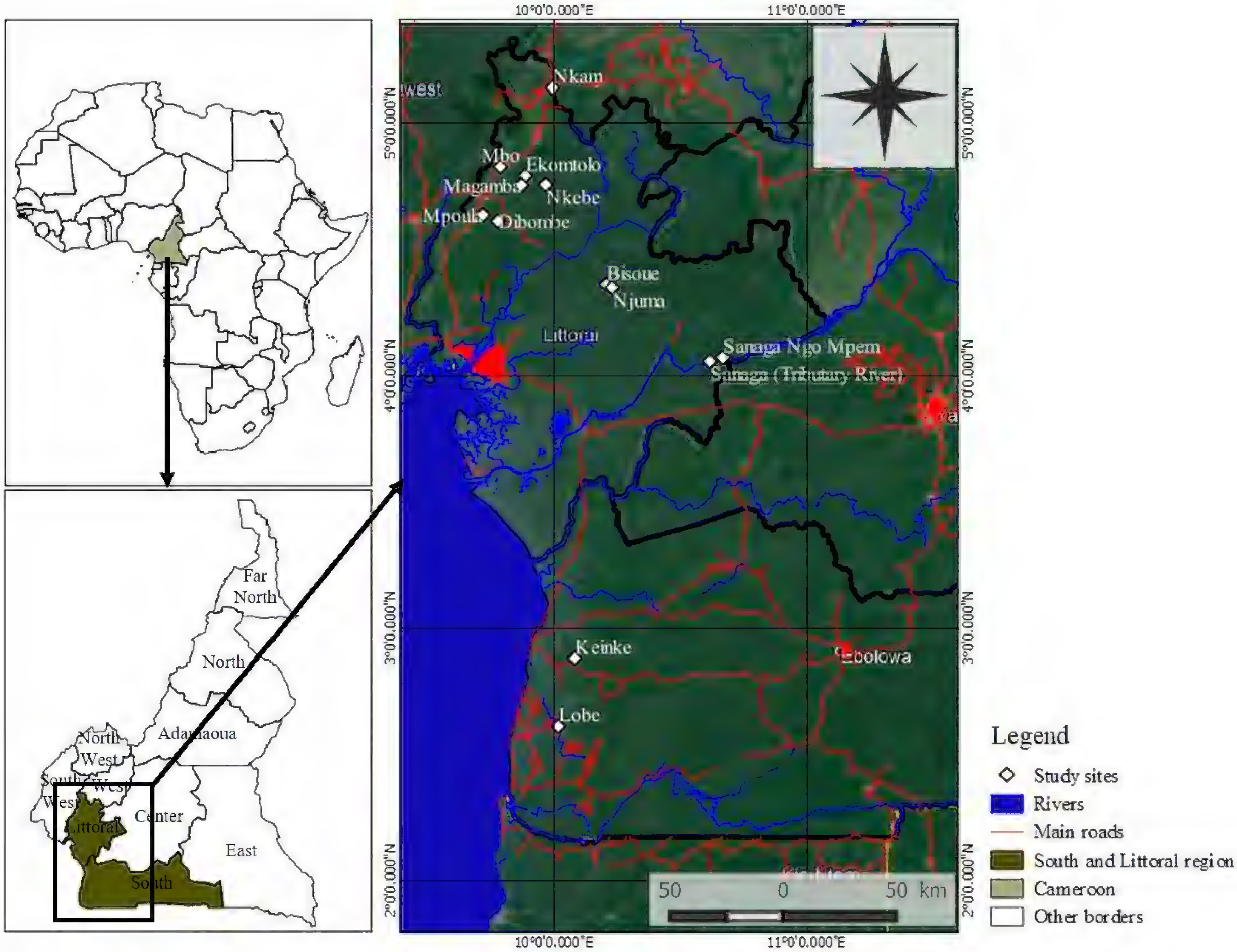

Fig. 1. Map of Cameroon indicating the locations of the study sites.

population for house construction or for local trade. Many footpaths, as well as the remains of abandoned logs, snare traps, and rifle cartridges, were found within these forests, indicating ongoing and constant use for hunting and timber exploitation. Secondary Forest comprised ten segment portions of the 13 rivers surveyed.

Agroforestry Plantations (AP) included all plantations, ranging from small-scale subsidiary crops and/or cash crops cultivated by the local people to intensively farmed, large-scale monocultures created by international commercial agro-companies. This habitat type, especially when cultivated by local farmers, could include native trees with more or less open canopies (≤ 50%), the largest stem diameters exceeded 40 cm, and they were spaced all throughout the cropped species. Most of the cultivated plants were introduced species, including manioc (*Manihot esculenta*), papaya (*Carica papaya*), pineapple (*Ananas comosus*), mango (*Mangifera indica*), cocoa (*Theobroma cacao*), palm oil (*Elaeis guineensis*), avocado (*Persea americana*), and bananas (*Eumusa* spp.). Native large trees were found mostly in cocoa plantations as shade-trees, whereas banana tended to be cultivated in large monocultures. The latter is cultivated at a commercial scale in the Njombe-Penja area for exportation. Agroforestry Plantations comprised seven segment portions of the 13 rivers surveyed. To enhance crop production, herbicide and pesticide mixtures are prepared in nearby rivers and streams with likely runoff, polluting the rivers.

Sampling took place between 0700 and 1200 h, and included various microhabitats, such as waterfalls, rocky rapids, rock pools, and riverbanks, as well as forest strips up to 20 m from the rivers. Gaining access to the rivers and their banks demanded careful clearance of trails, e.g., removing of some lianas or dead wood along a narrow trail. Trails were set-up at least 24 h before surveying the respective area. To maximize the probability of documenting all individual frogs, teams of two or three researchers walked along the rivers at a slow, steady rate of 0.2 m per second, avoiding any jerky movements that could disturb the frogs. Headlamps and handheld flashlights were used to detect the frogs, particularly by picking up eye-shine. All spatial data were recorded with a Garmin GPS (60 cx; accuracy of 5–10 m). For every frog, the perch site, date, time, posture, size, and distance from the riverbed were recorded. Size categories were classified as follows: adults (≥ 19 cm snout-vent length) (Fig. 3A); subadults (approx. 10–18 cm) (Fig. 3B); and juveniles (≤ 9 cm) (Fig. 3C).

Daytime habitat assessments preceded the nighttime

Fig. 2. Examples of the three different forest types investigated in this study: **(A)** primary forest (River Dibombe), **(B)** secondary forest (River Nkam), and **(C)** agroforestry plantations (River Mpoula).

surveys, with notes taken on habitat features, such as dominant vegetation, as well as notable, anthropogenic influences on the sites. Notes on the microhabitats of sun-basking frogs were made accordingly. Data for the daytime searches are not generally comparable to the nighttime searches, given that the frogs are mostly active during the night. However, the locations of daytime frog encounters regularly coincided with the presence of similarly-sized individuals during the night.

Local Ecological Knowledge (LEK) was obtained from local frog hunters around the surveyed areas who could reliably identify Goliath Frogs and regularly hunt them. This information was collected through informal interviews and discussions, and it greatly contributed to our assessments. To prevent any biasing toward certain answers, we asked all of the respondents the following six questions: Which are the rivers where Goliath Frogs are present? How far are they from the village? What was your biggest catch ever, and when was that? What was your biggest catch in 2019? How often do you hunt for the frogs? What is your perception about the Goliath Frog population around the village?

Data Analysis

The sampling effort was recorded only for the nocturnal surveys. Daytime searches were not time constrained as they were mostly meant to identify nocturnal survey sites. Sampling effort is given in person-hours, i.e., the number of hours spent surveying multiplied by the number of observers for any given river and habitat type (Table 2). The relative abundance of frogs was calculated as the number of individuals observed per time unit, divided by the number of sightings through the total sampling effort for each river or habitat type, and given as frogs per person-hour. As the relative abundances of Goliath Frogs were not normally distributed, Pearson's Correlation Coefficient was applied to compare the abundance of frogs and age groups per habitat type.

In order to examine frog abundance in relation to human presence, the GPS coordinates of the study sites were used and a 10 km buffer around each point was drawn in a geo-information system (QGIS Development Team 2021). All streets and settlements within the buffer zone were extracted from the Open Street Map database (https://planet.openstreetmap.org), and the total length of all roads (motorways, interregional and regional highways, urban as well as agricultural roads) was determined, as well as the number and type of settlements. No recent, fine-scale census data are available for the study area, thus the human population within each buffer zone was estimated by assigning fixed values to each of the different settlement types. Hamlets, the smallest type of settlement, accounted for 200 people, villages for 1,500, towns for 25,000, and cities for 100,000 inhabitants. Note that these values were

Fig. 3. The three different age sizes of Goliath Frogs considered in this study: **(A)** adult (≥ 19 cm), **(B)** subadult (10–18 cm), and **(C)** juvenile (≤ 9 cm).

based on the open street maps criteria. Human population density was calculated by dividing total population by the area within the 10 km radius buffer zone (314 km²). The distance of each sampling site to the nearest road and settlement boundary were determined. Subsequently, the data were screened for any linear dependencies of the GIS extracted values and the number of observed frogs (*iph*) in a regression analysis. Distance measures were log-transformed before the analysis.

To analyze the LEK data, a Welch-test comparing the hunter's perceived frog weights in different years was performed. A linear regression model was used to determine if there was a correlation between frog weight measured by local hunters and distance to the nearest settlement. All analyses were conducted using R v.4.0.0 (R Development Core Team 2014).

Results

Encounter Rates and Distances to Settlements and Roads

A total of a 100 person-hours were spent surveying for Goliath Frogs at 13 rivers across the entire range of the species in southwestern Cameroon. During the study, 490 frogs were observed along 26.7 km of riverine habitats, including 13.1 km in PF, 7.0 km in SF, and 6.6 km in AP. The number of person-hours spent on each habitat type varied, given the differences in river size and habitat accessibility. The encounter rates of frogs varied with respect to habitat types, rivers, and with grade of anthropogenic influence. For the entire study period, the average encounter rate was five frogs per person-hour (5 *iph*). Within the three habitat types, the highest mean *iph* was 8.2 recorded in SF, followed by 7.1 in PF, and 4.6 in AP. However, these values were not statistically different (Fig. 4). The two individual study sites with the highest encounter rates (17.0 *iph*) were both in SF, along the Sanaga and Keinke rivers. At these sites, the forest had been legally and commercially logged. These localities are far from human settlements and the frogs seemed to show lower flight-distances when approached compared to the frogs at other sites (however, we did not collected data to support this general impression). The lowest encounter rates were along the Ekomtolo and Mpoula Rivers (1.0 *iph*), and both localities are close to human settlements. Although disturbed, the surveyed portion of Mbo River, which is bordered by about 50% AP, revealed very high encounter rates (8.4 *iph*).

Human densities and the levels of anthropogenic disturbance varied considerably around the study sites. Total road length within a 10 km radius buffer around the sites ranged between 9 km and 168 km, with a mean of 84.5 km. The number of settlements ranged from 1 to 20 within the buffers, with a mean value of 10.1. The estimated human population densities ranged from

Table 2. Encounter rates of Goliath Frogs (in person-hours of searching effort) during time-constrained visual encounter surveys in the three different habitat types: PF, primary forest; SF, secondary forest; and AP, agroforestry plantation. Data are given for each of three different age sizes: a, adult; s, subadult; and j, juvenile.

Habitat type	**PF**				**SF**				**AP**			
Age size	**a**	**s**	**j**	**Σ**	**a**	**s**	**j**	**Σ**	**a**	**s**	**j**	**Σ**
Lobe					7.20	2.40	0.00	**9.60**	4.00	6.00	0.00	**10.00**
Nkebe	2.07	1.33	0.93	**4.33**	2.75	2.25	0.50	**5.50**				
Ekomtolo					1.00	0.00	0.00	**1.00**	1.80	0.80	0.20	**2.80**
Dibombe	3.50	2.33	1.33	**7.17**	3.00	1.88	4.13	**9.00**	2.00	2.50	0.00	**4.50**
Sanaga Ngo Mpem	2.40	1.05	1.05	**4.50**	2.77	2.08	1.62	**6.46**				
Sanaga (Tributary River)	6.43	4.29	1.71	**12.43**	9.00	6.50	1.50	**17.00**				
Keinke	3.67	5.67	1.33	**10.67**	9.00	7.50	0.00	**16.50**				
Magamba									0.89	0.78	0.33	**2.00**
Nkam					4.29	2.57	0.00	**6.86**	2.63	1.50	0.00	**4.13**
Mbo					4.20	1.20	1.20	**6.60**	2.40	4.20	1.80	**8.40**
Mpoula					2.17	0.33	1.00	**3.50**	0.44	0.00	0.22	**0.67**
Njuma	1.63	1.25	0.00	**2.88**								
Bisoue	3.38	4.50	0.00	**7.88**								
Mean	**3.29**	**2.92**	**0.91**	**7.12**	**4.54**	**2.67**	**0.99**	**8.20**	**2.02**	**2.25**	**0.37**	**4.64**

1,000 to 99,200 inhabitants in the 314 km² of the buffer zones (12.7–1,263.7 persons per km²), with a mean value of 32,592.3 (415.2 persons per km²). Road length and population density were negatively, but not significantly, associated with higher frog numbers (Table 3). The distances between study sites and the nearest settlement ranged from 89 to 9,114 m (median = 2,741 m), and the distances between study sites and the nearest road ranged from 176 to 8,653 m (median = 701 m). While both measures (after logarithmic transformation) indicated a positive association between distance and frog numbers, only the nearest settlement showed a robust and significant linear dependency (Table 3, Fig. 5). In other words, more frogs were found when the nearest settlement was farther away. Only the Njuma River violated this rule, as it was the most remote site but only provided a small number of frogs (Table 3).

Age Categories and Microhabitats

Of the 490 Goliath Frog observations, 243 (49%) were adults, 170 (35%) were subadults, and 77 (16%) were juveniles. Of all the adults, 48% where from PF, 36% from SF, and 16% from AP. The encounter rates of the three age sizes varied among the rivers, as well as both between and within the different habitat types. A Chi-square test of the three age groups showed that there was no difference in the population structures between the three different habitat types ($\chi^2 = 3.48$, $df = 2$, $p = 0.48$). The highest encounter rates among the three age sizes were for adults (9.0 *iph*) recorded in SF; while the lowest was in juveniles (1.0 *iph*) recorded in all three habitats (PF, SF, and AP). The recorded encounter rates of the frogs, sorted by age sizes within the three surveyed habitat types, are summarized in Table 4.

Goliath Frogs showed a patchy distribution across the study sites and were mostly restricted to particular microhabitats, which included moderate to fast flowing rivers with cascading, turbulent rocky sections (Fig. 6), or waterfalls with mostly sandy soils. The species was recorded from Bifa, Babong, Ekomtolo, Magamba, Manengotang, Nko-Olong, Ngo-Mpen, Nkongsou, and Sole. The altitudinal range of the inhabited sites spanned from 39 m asl at Lobe River around Bifa and near the coast, to about 677 m asl at Nkam River. Goliath Frogs were recorded in 75% of the surveyed rivers, but only when these included suitable microhabitats. The inhabited river sections surveyed varied from 50 m to more than 300 m. The torrent, rocky sections were inhabited while the in-between sections, slow moving, meandering river parts with no rocks, revealed no frogs. Goliath Frogs were completely absent from rivers lacking fast flowing sections and rocks. For example, the five rivers south of the newly constructed deep-sea port at Kribi that were investigated all lacked the above-mentioned microhabitats, and yielded no Goliath Frogs despite being within the range of the species. Discussions with local ethnic groups, including the Bagyli/Bakola people who have lived in this forest for many generations, confirmed that Goliath Frogs never occurred in this area.

Age dependent differences were noted in microhabitat use. When Goliath Frogs came out at night to perch on rocks, the adults used the areas around large cascading waterfalls, while sub-adults were more often present on rocks in the rapids, and juveniles inhabited rock pools and crevices. Adult frogs were abundant around waterfalls

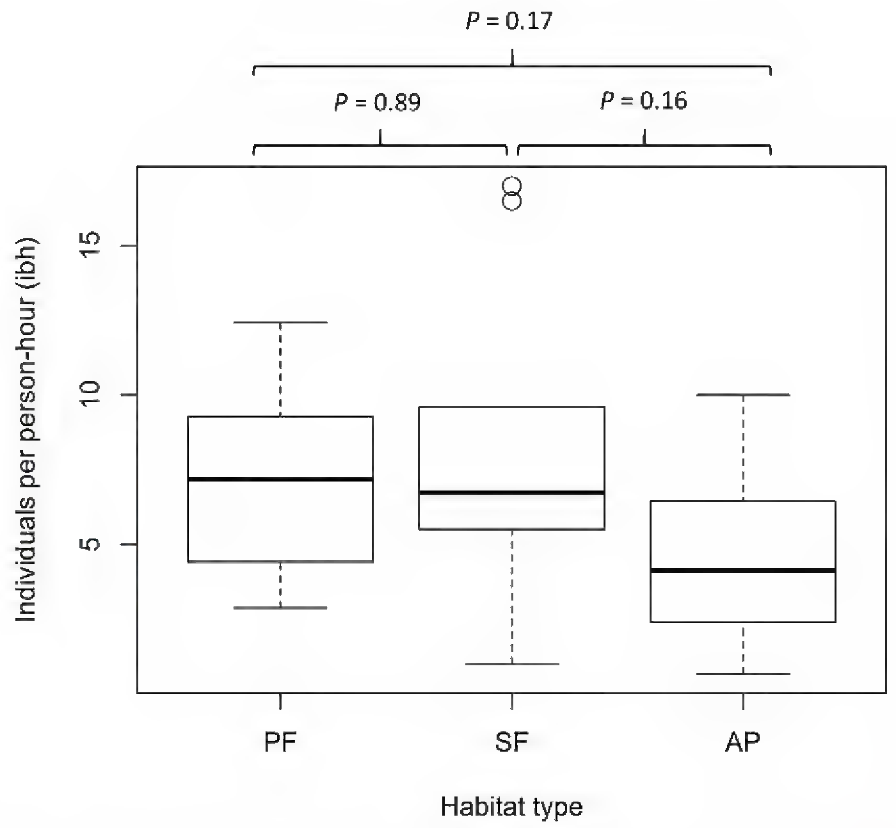

Fig. 4. Number of individual Goliath Frogs recorded per person-hour in each of the three surveyed habitat types: PF = primary forest; SF = secondary forest; AP = agroforestry plantation. Note that the encounter rates of frogs were not statistically different between any of the three habitat types.

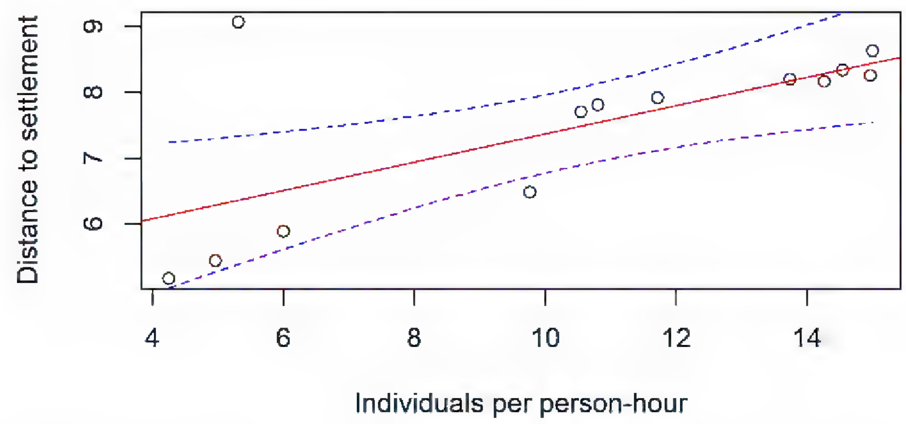

Fig. 5. Scatterplot of Goliath frog abundance (as individuals per person-hour) and log transformed distance to the nearest settlement. The red line is the trendline of the fitted linear model and the blue dotted lines demarcate the 95% confidence interval. Note that the top outlier point refers to Njuma River, which was the most remote site sampled, however, it also accounted for one of the lowest numbers of individuals.

Fig. 6. Typical forested and rocky-sandy riverbed characteristics for Goliath Frog habitat (Dibombe River).

but maintained some distance from one another. The closest distance between two adult frogs was 3 m, observed at Dibombe River. A maximum of seven adult individuals were observed at a single waterfall along Nkebe River. On Mpoula River, adult frogs were seen sitting on large branches within jumping distance of the stream (~5 m in adult frogs), at more than 2 m above the ground. At night, adult frogs that had fled from the surveyors by diving into the stream returned to the same perching rocks shortly (10 to 15 min) after disturbance, indicating fidelity to particular perching sites. Adults and subadults ($n = 24$) were frequently observed at night on low bushes and trees more than 10 m away from the riverbed. During the daytime, our observations revealed extensive sun-basking behavior, i.e., more than 20 adults were seen sun-basking throughout the study period. Adults often leaped and dove into the rivers upon our approach (flight distance 4 to 10 m). One individual was observed basking on the same rock on three consecutive days, along a relatively calm portion of Ekomtolo River. When disturbed, this frog jumped into the river and returned to its perch site after about 30 to 45 min.

Presence at Sites Impacted by Pollution and Agricultural Activities

The data revealed that Goliath Frogs persist in forest fragments, plantations, and rivers, even when surrounded by human settlements. Observations from the localities of Magamba and Manengotang indicate that small populations can be present at about 200 m from human settlements. Here, the habitat was patchy and comprised a mosaic of small forest remnants and small subsidiary plantations. The Goliath Frog occurrence at these places was also confirmed by Goliath Frog hunters, and frog hunting at these sites was perpetual. We commonly observed habitat pollution by the dumping of household waste into the rivers and adjacent forests. Unfortunately, there is no quantitative data regarding how long the habitats had been impacted (by logging and/or pollution); for how long and with what intensity the frogs had been/are being hunted; or how large the populations had been previously and how they had developed. Thus, there is no way to estimate how long these populations may prevail despite the small numbers of individuals and altered habitats.

The vast majority of the local people (~70%) around the study sites live on subsidiary and cash crop agriculture. In the study area, many forests along large rivers and streams have been transformed into cocoa and palm oil plantations, with larger portions converted where populations are high. To maintain these plantations and to improve production, fertilizers, herbicides, fungicides, and insecticides are used extensively. The preparation of those chemicals generally happens along the nearby rivers and streams, inevitably contaminating the water (NLG, pers. obs.). The scale of these potential threats

Table 3. Sample sites, numbers of frogs, and extracted values for number of roads, total length of roads, number of settlements, derived population estimate within the 10-km buffer zone, as well as measured distances to nearest settlement and road. Correlation coefficient and *P*-values from correlation analysis are given below each of the respective measures.

River	IPH	Total length of roads	Distance to nearest road	Distance to nearest settlement	Number of settlements	Population estimate
Lobe	9.77	167.9	650.9	701.26	5	1,000
Keinke	11.72	86.6	2,741.1	2,941.09	6	9,000
Dibombe	14.26	78.2	3,508.5	525.02	6	9,000
Bisoue	15.00	23.8	5,624.6	6,126.63	1	1,500
Mpoula	10.80	131.7	2,464.6	505.07	10	85,500
Nkebe	13.74	31.8	3,634.7	2,372.22	7	10,500
Sanaga (N)	10.55	69.4	2,199.6	2,236.13	5	31,000
Sanaga (T)	14.55	82.5	4,175.9	5,603.30	19	28,500
Njuma	5.31	8.9	8,653.5	9,113.55	1	1,500
Magamba	6.00	80.5	358.8	149.07	17	25,500
Ekomtolo	4.25	94.6	175.8	89.25	19	75,500
Mbo	14.97	82.2	3,843.3	541.14	15	46,000
Nkam	4.96	160.1	229.9	477.44	20	99,200
R^2		-0.257	0.688	0.431	-0.304	-0.415
P		0.3972	**0.0093**	0.1410	0.3130	0.1590

to the frogs varied through the study sites and time. Along the river at Magamba for instance, large quantities (estimated at around 70%) of the original forest were transformed into plantations within our six-year survey period. Nevertheless, the Goliath Frog populations persisted at these sites.

Frog Size and Distance to Settlements

Frog size, estimated by the authors and the surveyed hunters, was positively correlated with distance to settlements, with smaller frogs living closer to the settlements (Fig. 7). Discussions with 11 frog hunters revealed that they have to move increasing distances of 300 to 4,000 m from the settlement in order to find large frogs, and that the adult and subadult/juvenile Goliath Frogs, which were once common around waterfalls and rock pools, are now less abundant. Based on weight estimates from the hunters, they agreed that the largest Goliath Frog they ever encountered, estimated to weigh about 5 kg, was caught before the year 2010. There was a significant (Welch-test: $t = 6.14$, $df = 15.87$, $p < 0.0001$) drop in the perceived frog weight when compared to the largest frog caught in 2019 (Fig. 8).

Discussion

This study assessed Goliath Frog habitats and relative abundance over large parts of the known range of this species in Cameroon, in order to understand the influences of land use and vicinity to human settlements. Goliath Frogs were found to occur within all of the three main habitat types surveyed, i.e., primary forest, secondary forest, and agroforestry plantations. The frogs utilize a combination of particular microhabitats that are stratified by different age sizes. Torrent water and rocks seem to be requirements for the presence of all ages. Based on our data, Goliath Frogs seem to be able to deal with some degree of habitat alteration, and the population decline is mostly due to hunting.

Impacts of Anthropogenic Factors

Due to the lack of previous (quantitative) data, it is difficult to reliably assess whether and to what extent the Goliath Frog populations have changed. Therefore, we had to base our assessment on indirect evidence, e.g., the comparisons of frog occurrences in pristine versus altered habitats, the severity of different threats, and interviews with local frog hunters. One exception is the previously published data on the abundance of Goliath Frogs along the Sanaga River, described by Perret (1957, 1960) and Amiet and Perret (1969). These populations still persist today, despite the high degree of selective logging in the area. However, this positive finding does not preclude the fact that the species seems to be threatened by human activities in general, and the situation for many local populations is not very promising. We base this conclusion on our observation that especially large adult frogs are rare around human settlements and increase progressively farther away, a basic finding confirmed by the surveyed frog hunters. Two indirect measures of anthropogenic impact, roads and population densities, indicated a trend of increasing frog numbers with the remoteness of habitats, although only frog abundance and distance to settlement was robustly, positively correlated.

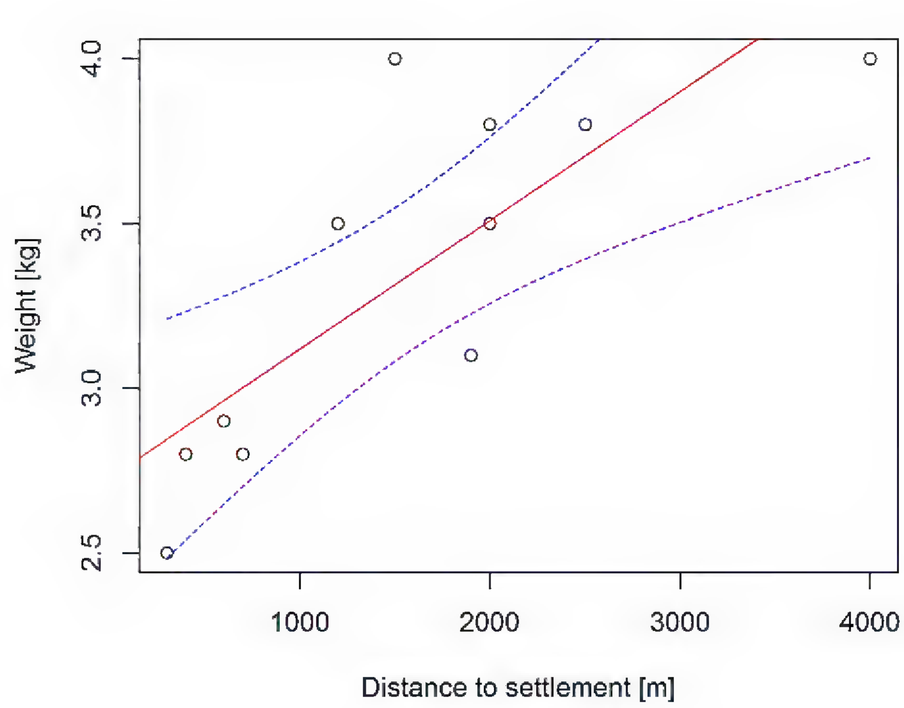

Fig. 7. Scatterplot of frog weight and distance to the nearest settlement. Note that the weight of the Goliath Frogs was increasing with distance from human settlements.

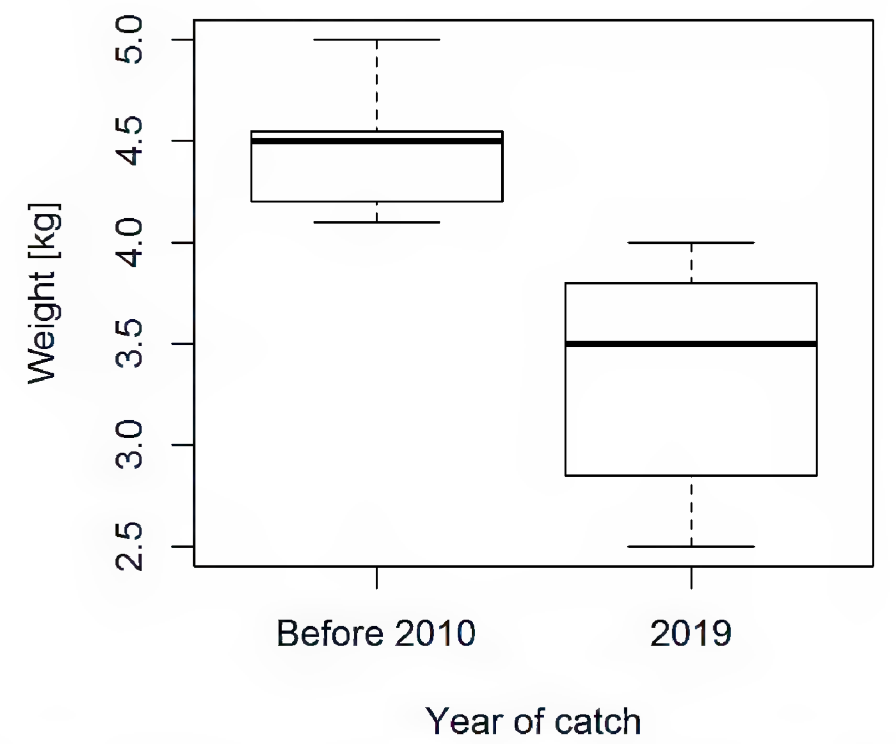

Fig. 8. Changes in weight of Goliath Frogs from around 1990 to 2019, as estimated by the surveyed frog hunters.

This analysis has some limitations. First, there are limitations in the dataset itself. For instance, we are certain that not all small settlements and roads were consistently recorded, and thus the human impact may be generally larger. Our population estimates include some errors and inaccuracies as well, e.g., the population for the category 'village' in OpenStreetMap ranges from 500–5,000. Clearly not every village will have a population of about 1,500 inhabitants. Nonetheless, our data generally indicated coherent patterns. The Goliath Frog population of Lobe, for instance, is situated right next to a vast banana plantation and gave the lowest frog population estimate. On the other hand, several Goliath Frog populations were quite large despite being in close proximity to major roads. Generally, the distance to the nearest settlement was a better predictor for frog abundance.

The impact of distance to the nearest settlement was especially notable for populations that are exploited for food and trade, and also comprise anthropogenic impacted habitats. For instance, the Nkongsamba area has undergone a drastic change in vegetation structure over the past decades, as large-scale agro-industrial plantations and an increasing number of subsistence plantations have

Table 4. Counts of the Goliath Frogs observed in the 13 rivers for the three habitat types (PF, primary forest; SF, secondary forest; AP, agroforestry plantation) across its range in Cameroon. Count data are provided with respect to the three different age sizes: a, adult; s, subadult; and j, juvenile.

River	Count data (numbers of observed individuals)												
	PF				SF				AP				Total
	a	s	j	Σ	a	s	j	Σ	a	s	j	Σ	
Lobe					6	2		**8**	2	3		**5**	13
Nkebe	31	20	14	**65**	11	9	2	**22**					87
Ekomtolo					3			**3**	9	4	1	**14**	17
Dibombe	21	14	8	**43**	8	5	11	**24**	4	5		**9**	76
Sanaga Ngo Mpem	16	7	7	**30**	12	9	7	**28**					58
Sanaga (Tributary River)	15	10	4	**29**	18	13	3	**34**					63
Keinke	11	17	4	**32**	6	5		**11**					43
Magamba									8	7	3	**18**	18
Nkam					5	3		**8**	7	4		**11**	19
Mbo					7	2	2	**11**	4	7	3	**14**	25
Mpoula					13	2	6	**21**	4		2	**6**	27
Njuma	13	10		**23**									23
Bisoue	9	12		**21**									21
Total	**116**	**90**	**37**	**243**	**89**	**50**	**31**	**170**	**38**	**30**	**9**	**77**	**490**

been established (NLG, pers. obs.). In this area, Goliath Frogs are also intensively hunted for the food market. This is the area where we recorded the lowest encounter rates throughout the entire study period. Habitat conversion and degradation usually went hand in hand with hunting pressure, with both being more pronounced close to settlements. Around the localities of the Ebo forest, anthropogenic pressure was almost absent, and here we encountered the highest numbers of frogs per survey effort.

Importance of Forest Habitats

In contrast to the human impact, vegetation type was not a useful predictor, as Goliath Frogs were present in all forest types from semi-open to close-canopy forests (as long as cascading rocky river sections were present). Goliath Frogs apparently need some forest, but not necessarily pristine forest. They live in cold water and regularly sun-bask, presumably to regulate body temperature. Thus, the opening of forest habitats and resulting raising of temperatures may not negatively impact them, as long as the water temperature remains "low enough" (although, unfortunately, the temperature preferences of the species are unknown) and the habitat surrounding the rivers can still provide enough food and shelter. Other African frog species with similar life-histories and inhabiting forested, torrent rivers, e.g., *Conraua alleni* and *Odontobatrachus* spp., also usually occur in cooler streams in forest, but may persist in areas with little riverine forest surrounded by savanna (Rödel 2003; Rödel and Bangoura 2004).

In this survey, when cascading, turbulent water with rocks and some forest patches was present, Goliath Frogs were reliably recorded. Thus, Goliath Frogs may be able to tolerate forest degradation to a surprising extent. This is in line with predictions by Hirschfeld and Rödel (2017) that large frogs in particular, with large clutch sizes and aquatic larvae, may be more resilient to forest degradation than species with other trait combinations. We would like to stress, however, that our observations should not be interpreted as indicating that riverine vegetation is not important for maintaining Goliath Frog populations.

Riverine forest may be important for Goliath Frogs during their nocturnal foraging activity. It is likely that all individuals observed along the river banks were adopting a 'sit and wait' foraging strategy. A study on stomach and intestinal contents revealed that the diet of *C. goliath* consists of approximately 60% arthropods, 20% crustaceans, 10% amphibians, and 10% indeterminate food items, the latter comprising ingested stones as well as pieces of wood and leaves (Sabater-Pi 1985). The majority of the arthropods were terrestrial taxa. The presence of leaves, wood, and stones also suggests a mainly terrestrial foraging mode. If the quality of the riparian forests impacts prey quality and quantity, this would likely impact the Goliath Frog populations as well.

Our observations on one particular frog highlight the Goliath Frog's use of riverine forest habitats. In primary forest along Nkebe River, a large adult was found in the forest leaf litter at about 14 m from the river. When disturbed, the frog covered this distance with three long jumps back to the river (also see Herrmann and Edwards 2006). In about 1 m water depth, the frog could then be spotted in the slow flowing, clear water. Further disturbance (with the torch beam) triggered the frog to bury itself deep in the sandy and leaf-littered river bottom until it could not be seen anymore, a behavior also known from its smaller congener, *C. crassipes* (Knoepffler 1985). Goliath Frogs are less active during the day, and when encountered, they were usually found sun-basking. When disturbed, the behavior was the same as during the night, with the frog seeking shelter in the water or beneath the rocks it was sitting on.

Use of Microhabitats by the Different Age Classes

Our observations revealed that Goliath Frogs partition microhabitats by age-class. Therefore, a range of different riverine habitat features is likely crucial for supporting the full complement of life stages of this species. Large adults predominately perched on rocks around waterfalls and rapids, with individual separated by a considerable distance (minimum 3–5 m), thereby providing evidence for territorialism and site fidelity, as already suggested by Sabater-Pi (1985). In contrast, subadults were rarely found around waterfalls. They appeared frequently on exposed, mid-stream rocks in the vicinity of cascades and waterfalls. Finally, metamorphosing and juvenile frogs most often used rook pools along the riverbeds where the current was slower. There they could find refuge in rock crevices when disturbed (Fig. 3C). Such sections also comprise the breeding sites of the species (Sabater-Pi 1985; Schäfer et al. 2019). The reason for this microhabitat partitioning is unclear. It may be a linked to thermoregulation, with small juveniles avoiding colder water, and/or predation pressure, including cannibalism. Habitat segregation has been reported from juvenile/subadult and adult European water frogs, *Pelophylax* spp., in order to escape cannibalism (Günther 1990).

Based on daytime observations, Sabater-Pi (1985) estimated the territory sizes of 20 to 40 m^2 for Goliath Frogs along the Mbia River. Our observations suggest that Goliath Frogs use small core areas or territories for sun-basking and shelter (200 m^2), and larger areas (> 1,000 m^2) for foraging. However, quantitative research on this issue is lacking and ideally should be based on radio-tracked individuals (e.g., Spieler 1997).

One surprising finding of this study was that the Goliath Frogs showed no apparent impact from the contamination with agrochemicals from neighboring plantations (at least to the extent that it is represented in our study sites; although, unfortunately, the composition and quantity of agrochemical run-off in the streams is unknown). On the Mpoula River, a large banana plantation that is regularly sprayed by airplane occurs just upstream from where the Goliath Frogs were observed. In most of the study areas, small to medium-sized plantations along the rivers are run by local farmers. They typically use small spraying pumps and regularly process chemicals in the rivers, and the Goliath Frogs could still be found at these sites. Our observations, as well as the information from the frog hunters, revealed that populations around human settlements are smaller and adult frogs are rarer. As habitat degradation seemed to be of little influence, the Goliath Frogs might be mainly impacted by targeted hunting for food (locally) and trade.

Conservation Needs of the Goliath Frog

In order to detect potential declines, populations should be monitored on a regularly basis. However, no national monitoring program for Goliath Frog populations has been implemented thus far. Long-term data collection from specific sites across the Goliath Frog range would be essential for detecting changes in the distribution and local abundances of this species. Standard guidelines and techniques for monitoring amphibian populations and habitats are well-established (e.g., Heyer et al. 1994). Potential monitoring methods for Goliath Frogs should include time-area constrained searches in order to establish baseline data against which population changes with time could be judged. The data presented here may serve as a baseline for future studies. Based on our findings, regular surveys carried out at night by walking along pre-defined river routes would probably be the most efficient method. The Nkongsamba area is especially critical for monitoring because of the particularly intensive frog collection for food, and the severe habitat degradation overall. The Campo-Ma'an National Park and the Ebo Forest National Park should likewise be considered for monitoring, as they consist of areas with limited human impact. Monitoring in different parts of the species range will allow comparisons of the population trends within and outside protected areas. This will also potentially allow differentiation between the different threats such as collection, habitat degradation and pollution, climate change, and disease. Given that most amphibian populations naturally fluctuate (Pechmann et al. 1991), it would be ideal to start an initial monitoring program for at least five years.

Several key aspects of Goliath Frog ecology remain to be investigated in order to better understand the biology of this species (i.e., larval and juvenile survival rates, growth rates, age at maturity, and the longevity of adults). Such information may ultimately help in setting up a conservation action and management plan for this species. In parallel, additional short-term surveys (detecting as many populations as possible) and long-term monitoring data (to follow population trends) are needed to fully interpret the Goliath Frog's occurrences and threat status. This study has shown that conservation efforts for the Goliath Frog do not need to be prioritized for terrestrial habitat loss, but that hunting is clearly a prominent factor affecting the persistence of robust populations.

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